

# SOWER: Self-Organizing Wireless Network for Messaging

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## ABSTRACT

Short Message Service (SMS) has become extremely popular in many countries, and represents a multi-billion dollars market. Yet many consumers consider that the price cellular network operators charge for it is too high. In this paper, we explain that there exist alternatives to cellular networks for the provision of SMS. In particular, we present the Self-Organizing Wireless messaging nEtwoRk (SOWER), an all-wireless network operable in cities. In SOWER, each user installs a wireless, power-plugged, device at home and communicates by means of a mobile device. Based on our experimental measurements of IEEE 802.11 equipped devices, we show the feasibility of the concept in various urban scenarios. We also show that city-wide connectivity can be achieved even with a limited market penetration. We propose an appropriate routing protocol, and we explain that the capacity of such networks is sufficient to support messaging communication.

## Keywords

Ad hoc Networks, Messaging, Self-organization, Distributed Computing

## 1. INTRODUCTION

The operation of cellular networks is by far the largest business segment of mobile networking. In these networks, voice service is still the dominant source of revenue. Data services, however, are becoming more and more widespread; in particular, short message services (SMS) have become extremely popular. According to [34], they will account for a total revenue of \$84 billion of the cellular operators in 2008.

In spite of the fact that the provision of this service is relatively straightforward for the operators, in many countries the price of SMS usage is fairly high; consumer associations reproach the operators that they are taking advantage of their oligopolistic situation to maintain outrageous price rates [35]. The operators re-

spond that the cost of their overall infrastructure must be taken into account in the computation of a “fair” pricing scheme.

Much of the controversy is due to the absence of an alternative for the end users. In this paper, we will explain that this situation is about to change: alternatives to cellular networks are becoming available for the provision of messaging services; an important characteristic of these alternatives is that they can be partially or totally operated by the end users.

A first alternative consists in having a large number of end users open the access to their home-based Internet-connected WLAN access points (APs); in this way, mobile users passing by can connect to the APs to send and receive messages. The nice property of this solution is that it removes charging per message, as the connection of the AP to the Internet is usually charged at a flat rate; the amount of the messaging traffic would be negligible considering the available bitrate. But there are drawbacks: the operators of the Internet access may forbid (for example, for security reasons) this kind of open access; in addition, the person of the household managing the access point and paying for the Internet access subscription may be unwilling to open his personal communication and computing infrastructure to the SMS users of the neighborhood. Hence, the service availability provided by this alternative might be limited.

In this paper, we explore an all-wireless alternative: we show that a city-wide short message service can be supported by a user-operated wireless network, without using even one single wireline access. To our best knowledge, this solution was never studied so far.

The solution we propose is based on a two-tier architecture: a user is expected to install a fixed, power-plugged device at home, and to communicate via a hand-held

device; the home device keeps track of the location of the mobile one. The home devices organize themselves to set up a *wireless backbone* over which they transmit the messages. Each mobile device is attached to the wireless backbone via a nearby home device.

Of course, as we will see, if some home devices have also wireline connectivity to the Internet, this can only increase the performance of SOWER.

To demonstrate the feasibility of the solution, we report real connectivity measurements between IEEE 802.11 equipped laptops, that we have performed in a city. Based on the measurements, we estimate the device density and the market penetration required to reach network connectivity in various urban scenarios. We also propose an appropriate routing protocol that achieves the following goals: First, routing follows the “store-and-forward” principle, thus it is scalable and robust against temporary unavailability of communication links. Second, our routing scheme provides incentives for each user to operate her devices for the common interest of all users. Furthermore, we explain why capacity, well-known to have a major scalability problem in ad hoc networks, is sufficient to support messaging communication. Based on current market prices, we show in Section 8.2 that the proposed solution is cost-effective for the frequent SMS users.

The remainder of the paper is organized as follows. In Section 2, we give an overview of related work. In Section 3, we provide the description of our proposal for messaging networks. In Section 4, we present our results of connectivity and coverage in realistic scenarios. In Section 5, we propose a routing protocol suited to our messaging network proposal. In Section 6, we investigate capacity issues. More technical issues are presented in Section 7. We discuss the deployment of the network along with additional business issues in Section 8. Finally, we conclude our paper in Section 9.

## 2. RELATED WORK

In this section we overview the existing wireless network architectures and we discuss new wireless networks proposed in the literature.

### 2.1 Existing network architectures

Cellular networks, such as GSM networks, are the most prominent examples of existing wireless architectures [26]. These networks are typical examples of networks with *pre-deployed* infrastructure. Using a complex infrastructure, the network coverage can be almost 100 per cent in a given area. Cellular networks were originally designed to carry voice traffic, but the recent evolution towards new generations of cellular networks also enables data communication besides traditional voice

communication. The communication rate for both voice and data communication is low, compared to the data rate in computer networks.

Another example of existing wireless networks are paging networks [8]. These networks are used to provide one-way communication with short messages. The messages are used to notify the users, but users cannot reply to the notification. Like cellular networks, paging networks also rely on a pre-deployed infrastructure. Paging networks provide an almost full coverage as well. It is possible to have two-way communication with a paging system, but this requires a more sophisticated mobile device or a PC. Due to the messaging communication, the traffic rate is extremely low compared to that of the computer networks.

A different example of wireless networks is a Wi-Fi network [27]. These networks differ from cellular and paging networks in that they typically provide a coverage limited to a few access points, but with broadband access to the Internet. These *hot spots* are deployed in designated places, such as airports and train stations. Because of the limited coverage of the Wi-Fi network, users cannot change their place during the communication session. Current development efforts, such as the white paper [36], address the problem of seamless mobility in Wi-Fi access networks.

### 2.2 Proposed networks in the literature

Recently, novel wireless architectures have been proposed in the literature. Their main difference with respect to existing wireless networks is that they no longer depend on a pre-deployed, centrally managed infrastructure, but they operate in a self-organized manner. The most prominent example of these networks are ad hoc networks. In ad hoc networks, mobile devices perform all networking tasks (i.e., routing, packet forwarding) in a self-organized manner without relying on an existing infrastructure. The advantage of ad hoc networks is that they can be easily deployed at a low cost; the disadvantage is that they do not scale for all types of traffic. Notably, it has been shown in the work of Gupta and Kumar [7] that the capacity per user diminishes as the network size increases and that: “... scenarios envisaged in collections of smart homes, or networks with mostly close-range transactions and sparse long-range demands, are feasible.” In spite of this last sentence, the capacity problem described by the authors has been often interpreted as a result that shows the infeasibility of large scale ad hoc networks in general.

To overcome this problem, researchers proposed to combine ad hoc networks with existing infrastructures, such as cellular networks. This integration of cellular and ad hoc networks results in *hybrid ad hoc networks*. In

[18] Lin and Hsu present a multi-hop cellular architecture to extend the coverage of existing cellular system. Luo *et al.* describe a Unified Cellular and Ad Hoc Network (UCAN) framework in [20] that enhances control area throughput while maintaining fairness. The authors propose a fair 3G cellular base station scheduling protocol, an access discovery mechanism and a secure crediting system. In [31], Wu *et al.* present an Integrated Ad Hoc Cellular Relaying System (iCAR). The iCAR system can efficiently balance traffic loads between cells of the cellular system by using ad hoc relaying stations.

Several researchers proposed to replace the flat ad hoc network architecture with a hierarchical architecture. In the case of a hierarchical ad hoc network, there exists a backbone of wireless devices that have more powerful computation and transmission capabilities. Thus, they can relay the traffic coming from low-tier devices. Networking protocols can exploit the hierarchical structure of the network: Instead of a flat routing architecture, one can propose a clustered routing scheme (e.g., the solution proposed in [32]). In [16], Karrer, Sabharwal and Knightly propose a network based on pre-deployed Transit Access Points (TAPs), that serve as a high-speed, multi-hop, wireless backbone with a limited number of access points to the Internet. In [13], Jetcheva *et al.* propose Ad Hoc City, a city-wide, multi-tier ad hoc network based on vehicles. Small and Haas [29] describe an Infostation model (SWIM) that is based on the capacity-delay tradeoff of ad hoc networks. They demonstrate their solution on a system used to observe the behavior of whales.

## 2.3 Signal propagation

In Section 4, we will investigate connectivity in SOWER. Since connectivity depends on the radio propagation in the given environment, we briefly review the state of the art in this field.

Radio propagation has been extensively studied for cellular networks (for a comprehensive overview, the reader is referred to [26]). There exist several propagation models in urban environments for outdoor and also for indoor scenarios.

For outdoor signal propagation in urban areas, a widely used model is the Okumura model [21]. Okumura developed a set of curves giving the median attenuation relative to free space. Okumura's model is based on measured data and does not provide any analytical explanation. This model is applicable for frequencies in the range from 150 MHz to 1920 MHz and distances of 1 km to 100 km. Hata [11] formulated a corrected model based on empirical results for urban scenarios. The Hata-model is applicable for frequencies in the range

from 150 MHz to 1500 MHz. Unfortunately, neither the Okumura-Hata model nor its extension up to 2 GHz give precise propagation results for personal communication systems that have a communication range less than 1 km.

For indoor radio propagation, researchers use attenuation models derived from experiments. It is more difficult to define an appropriate propagation model for indoor than for outdoor, because propagation depends very much on the particular characteristics of the indoor environment. A detailed study of indoor propagation models is presented by Hasemi [9] and more recently by Hassan-Ali and Pahlavan [10]. Signal propagation and the effect of interference were also studied for the IEEE 802.11 system (e.g., [15]).

In the literature, there is currently no unified model that describes both outdoor and indoor radio propagation. In particular, there exist no analytical model to describe signal propagation from outdoor to indoor environment and vice versa. Propagation loss into buildings is determined by several factors, such as the number of windows, the material of the building and the vertical distance of the receiver from the sender.

## 3. AD HOC MESSAGING NETWORK

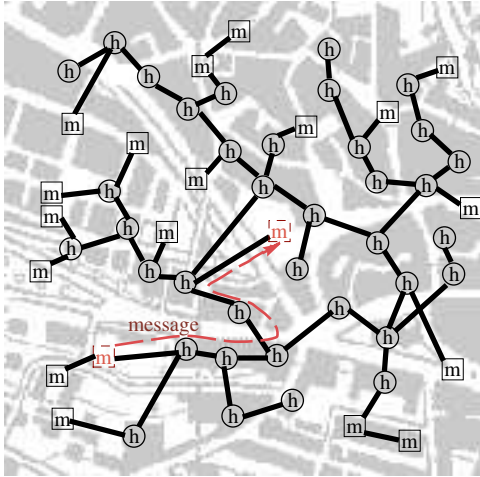
In this section we present our solution and discuss its properties in more detail.

### 3.1 System description

In this section, we propose a novel application scenario for ad hoc networks, which we call a *Self-Organizing Wireless messaging nEtwoRk (SOWER)*. We present an example of SOWER with a message transmission in Figure 1.

SOWER consists of two types of devices: a set of mobile devices and a set of static devices. We assume that each user owns two devices, one of each type. The user makes use of the first device as a hand-held device that we call a *mobile device*. We assume that the mobile device is powered by a rechargeable battery. We further assume that the user sets the second device at a fixed place connected to a permanent power source. Thus, we call the static device a *home device*. The deployment place for the home device is typically the home or the office of the user.

We make the following assumptions: All devices have similar radio capabilities. If two devices reside within the transmission range of each other, then they are considered to be neighbors. The devices periodically perform a neighbor discovery procedure, and are aware of their neighborhood. The radio links between neighbors are assumed to be bidirectional. All devices operate



**Figure 1: An example of SOWER: The network consist of a set of home devices (h) and mobile devices (m). The dashed line represents the route of a multi-hop message forwarding.**

in the same license-free ISM frequency band (e.g., at 2.4 GHz). Both mobile and home devices are equipped with a radio card that enables ad hoc networking. The devices rely on the CSMA/CA medium access method (e.g., IEEE 802.11b technology). Note that our proposal can rely on other technologies as well.

The devices form a wireless ad hoc network. The purpose of the ad hoc network is to provide *messaging communication* between the users. We call *message* the unit of user information that can be transmitted in a single packet (e.g., an SMS message in cellular networks or an email on the Internet). Message transfer between distant devices may involve multiple wireless hops. In our architecture, the mobile devices rely on the home devices to relay the traffic. We refer to the connected set of home devices as a *wireless backbone*. We assume that a routing protocol is implemented in each home device to transfer packets from the source to the destination. We also assume that a substantial amount of the traffic is limited to the city covered by the network.

In our proposal, we assume that the network is under the full control of the users, meaning that no central authority supervises the operation of the network. We will relax this assumption in Section 8. We assume, of course, that there exist companies that produce the wireless devices.

### 3.2 Discussion

Messaging does not requires strict latency guarantees. Hence, we propose a routing solution that is compliant with the “store-and-forward” principle. This simple so-

lution scales well, because it relies on the static wireless backbone provided by the home devices. Due to the static property of the wireless backbone, our routing proposal is light-weight and simple. Furthermore, home devices are energy-rich, thus, there is no incentive for the users to withhold contribution in order to save resources. It is also important that, unlike sharing existing Internet connections, our solution does not give open access to the personal computer of the users, only to their home device. Thus, no sensible personal data can be accessed.

## 4. CONNECTIVITY AND COVERAGE

In this section, we analyze the connectivity and coverage of SOWER in city scenarios. Our goal is to assess the required density of home devices in order to have a connected network<sup>1</sup>. We first present field test results for connectivity in a city scenario for radio propagation. Based on these results, we perform an extensive simulation study of connectivity in two-dimensional city scenarios. Finally, we extend our connectivity investigations to a three-dimensional area.

### 4.1 City scenario - Field test measurements

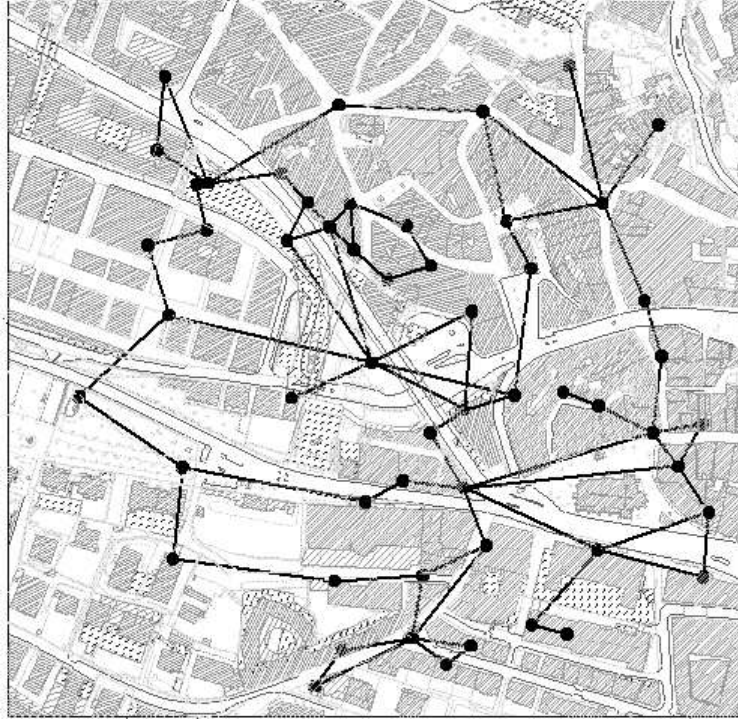
Although radio range is often modelled with a circle, this is obviously not an appropriate model in urban environments. None of the existing models presented in Section 2.3 can be used for our problem. Motivated by the lack of analytical results, we decided to perform a large number of connectivity measurements in a small city<sup>2</sup>. For this purpose, we used laptops equipped with Cisco Aironet [37] wireless cards. All wireless cards were compliant with the IEEE 802.11b standard. We operated the cards with a power of 100 mW, with the transmission rate set to “auto-rate selection” between 1 and 11 Mbit/s. We measured different types of links where we put the laptops indoors and outdoors.

We randomly chose measurement points in the center of the city to represent different types of links (as shown in Figure 2). We performed most of the tests in the streets and at the ground floor of the buildings. We also made some “vertical” measurements, meaning across the floors of the buildings. In our measurements, most of the devices reside indoor that is compliant with the properties of SOWER.

We identified different types of links that depend on the position of the endpoints and the type of propagation medium. The connectivity results for different

<sup>1</sup>The connectivity could be further increased by taking the mobile devices also into consideration. But we refrain from doing it, because it would result in higher power consumption on these battery-operated devices, and it would severely increase routing complexity.

<sup>2</sup>Name of the city is withheld to preserve anonymity.



**Figure 2: Map of the downtown area (500m \* 500m) with our connectivity measurement results. In our measurements, most of the devices reside indoor that is compliant with the properties of SOWER.**

types of possible links are shown in Table 1. The first two columns show the type of the link. We present the number of measurements in the third column. Columns 4 and 5 summarize the average value and standard deviation of the test results for each link type. The last column presents the simulated interval for radio range that is derived from the measurement results. The first row (the link type denoted by *I-I-O* and *I-O-O*) represents the link between an indoor device and an outdoor device. The second and third row represent the link between devices that reside in the same or in adjacent buildings, respectively. The radio signal propagates further in the outdoor environment, thus the first two link types are statistically longer. Note that the connectivity is affected by the material of the obstacles as well<sup>3</sup>.

Our measurement results also show that the small city center can be covered with a small number of devices. In our city, a network of approximately 55 devices are enough to cover the 500m \* 500m city center.

From our measurements in a small city, we generalize our results to a metropolis and suburban area using simulations. Although the structure of buildings is dif-

<sup>3</sup>Special material can break down the connectivity. In one of our measurements, the signal was not able to go through two special window glasses, but it could easily go through one.

ferent in a metropolis, a small city or a suburban area, there are common characteristics, such as the type of windows and doors. Radio signals propagate mainly through these light-weight elements in a building, making the generalization justified. In our future work, we intend to pursue a more extensive measurement campaign in different scenarios.

## 4.2 City scenario - Simulation results

We performed simulations using three different urban scenarios to assess connectivity in a two-dimensional area. We set the parameters of the generic model to represent three realistic city scenarios: (i) a metropolis with large buildings and wide avenues, (ii) a small city center with small streets and (iii) a suburban area including houses and open space. We defined the radio range in the simulations from the field-test measurements described in Section 4.1. All simulation results are the average of 100 runs with a confidence interval of 95%.

We used a simplified general city setting as shown in Figure 3. In the simulations, we generate a symmetric scenario of a total area of  $1 \text{ km}^2$  with a given street width (*SW*) and building width (*BW*). Table 2 summarizes the parameter values for the city scenarios. Our parameter settings correspond to the standard street width in urban street planning (e.g., [30]). The stan-

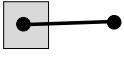
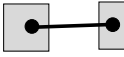
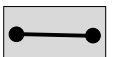
| Scenario (name) | Scenario (pictogram)  | Number of measurements | Average range | Standard deviation | Simulated range (Section 4.2) |
|-----------------|---|------------------------|---------------|--------------------|-------------------------------|
| <i>I-X-O</i>    |  | 26                     | 77.24 m       | 32.64 m            | 50-100 m                      |
| <i>I-O-I</i>    |  | 14                     | 71.75 m       | 27 m               | 50-100 m                      |
| <i>I-I-I</i>    |  | 12                     | 38 m          | 15.82 m            | 25-50 m                       |

Table 1: Connectivity measurements in a downtown scenario for different link types. “I” stands for indoor, “O” stands for outdoor and “X” stands for any of the two environments. The link *A-B-C* means: *A* - the type of the first end of the link, *B* - the type between the endpoints, *C* - the type of the second end of the link.

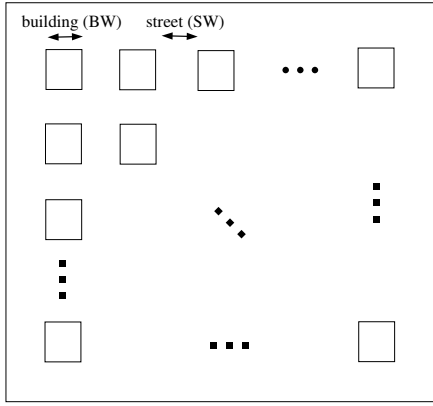


Figure 3: City scenario for connectivity and coverage experiments.

standard street size follows the standard design technique for city planning called *Transit Oriented Development (TOD)* [3]. In all simulations, we uniformly distribute the home devices among the buildings. We denote the *density of the home devices* by  $\delta$  throughout the paper and we express  $\delta$  in devices/ $\text{km}^2$ .

| Parameter | Metropolis | Small city | Suburban area |
|-----------|------------|------------|---------------|
| SW        | 40 m       | 20 m       | 35 m          |
| BW        | 80 m       | 50 m       | 13.25 m       |

Table 2: Parameter values for the city scenario coverage simulations.

In all cases, we consider the largest connected component of the set of home devices. We investigate the following performance measures:

1. Coverage of the largest connected compo-

nent (denoted by  $\kappa$ ):

$$\kappa = \frac{A_l}{A}$$

where  $A_l$  is the area covered by the largest connected component of home devices and  $A$  is the total simulation area.

2. Fraction of the number of devices in the largest connected component over the total number of devices (denoted by  $\pi$ ):

$$\pi = \frac{n_l}{n}$$

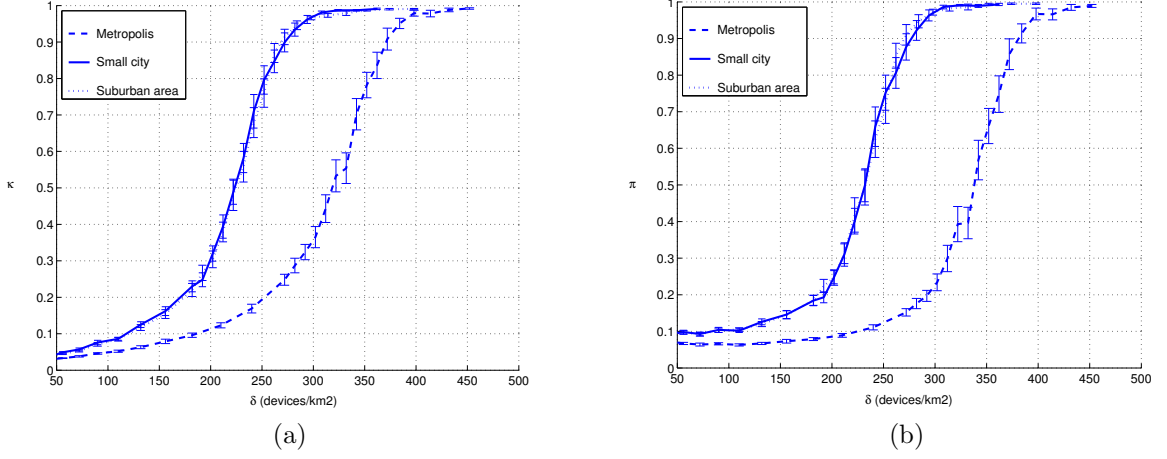
where  $n_l$  is the number of home devices in the largest connected component and  $n$  is the total number of home devices.

The connectivity for a given connection type is calculated from the measurement results presented in Section 4.1: The radio range for a device is a uniform random variable between the extreme values of that link type. This characterizes the fact that propagation loss varies with the material of the buildings.

First, we present our results for the coverage of the home devices. Figure 4a shows the value of  $\kappa$  as a function of the device density ( $\delta$ ) for all three scenarios.

We can observe that the coverage requirement for a small city and a suburban area is almost the same. In both scenarios, we can reach a coverage near to 100% with approximately 300 devices. In the metropolis, approximately 400 devices are needed to reach the full coverage. The full coverage is only possible if the network becomes almost fully connected. Figure 4b presents the value of  $\pi$  as a function of  $\delta$ .

The two-dimensional results are relevant in the subur-



**Figure 4: Coverage and connectivity in the two-dimensional network; (a) coverage of the largest connected component of home devices ( $\kappa$ ); (b) fraction of the size of the largest connected component and the total number of home devices ( $\pi$ ).**

ban scenario and in the small city scenario with low buildings. They are less relevant in the metropolis scenario, because in that case the network expands in three dimensions. To present more significant results for the metropolis scenario, we investigate the properties of a three-dimensional network in the following subsection.

### 4.3 Three dimensional network

In this section, we investigate the connectivity results for three-dimensional networks in the small city and metropolis scenarios.

According to our field tests, coverage in a building is typically 25-50 meters (depending on the environment), if both endpoints of the link reside on the same floor. Vertical coverage differs from the coverage on the same floor, because of the structure of the wall that is between the floors in a building. In our field test, we measured signal propagation in the vertical direction as well. Our test results show that a three-dimensional link *I-I-I* can cover 1 to 3 floors in a building if there are open areas between the floors, like moving stairs etc. According to our measurement results, considering an office building with very little open space between the floors, the vertical coverage of the link is at most one floor (e.g., 3-7 meters). If the devices are in a shopping center with big open areas and a big moving stairs, then the vertical coverage extends up to 3 floors (12-15 meters).

We present our simulation results for connectivity in the three-dimensional case<sup>4</sup>. We consider a small city scenario with buildings of 5 floors and three subtypes of the metropolis scenario, where buildings consist of 5, 30 and 50 floors, respectively. We randomly choose a building for each device with a uniform probability and

we also determine a uniformly random position within the building. We consider a three-dimensional network, where we extend the notion *I-O-I* links for adjacent floors in adjacent buildings. This means that a device located for example at floor 5 can communicate with devices that reside in floors 3, 4, 5 in an adjacent building, if they are within the given communication range defined for *I-O-I* links.

Figures 5a and 5b show connectivity results for small buildings and skyscrapers, respectively. In all cases, the simulation area is 1 km<sup>2</sup>. The connectivity, and therefore the coverage, of the network increases significantly if  $\delta$  is above a certain threshold.

Table 3 summarizes the device density requirements in the considered scenarios<sup>5</sup>. As a comparison, we present population density data from cities that represent the small city and three subtypes of the metropolis scenario, respectively (for the original data, see [38]):

- Small city center (e.g., Berkeley, California, USA) - small buildings with 5 floors
- Historic metropolis center (e.g., Rome, Italy) - large buildings with 5 floors
- Modern city center (e.g., Berlin, Germany) - large buildings with 30 floors

<sup>4</sup>For a large number of devices (i.e., if the number of devices increases over 2000), the simulation of coverage becomes infeasible. Hence, we present only connectivity results.

<sup>5</sup>Market penetration expresses the fraction of users in the network and the total population.



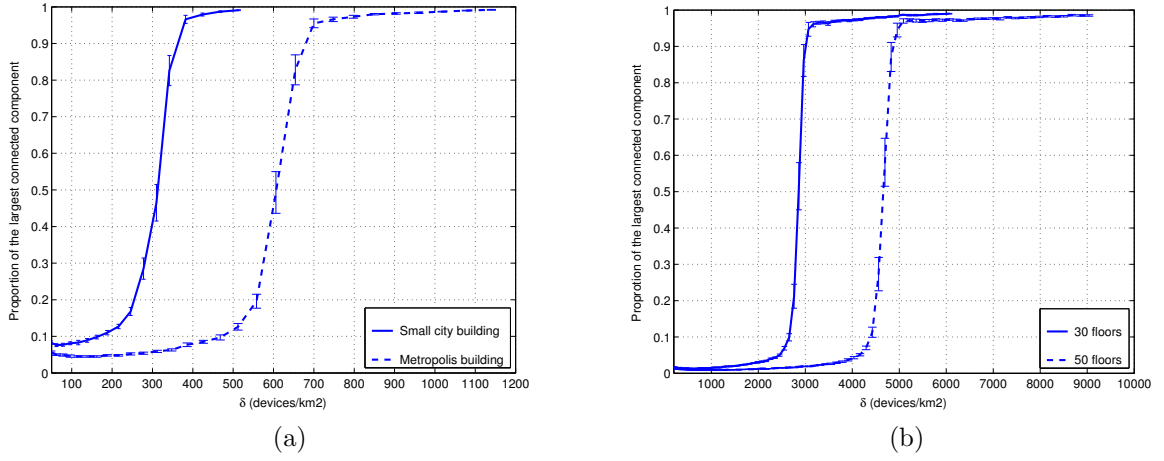


Figure 5: Fraction of the size of the largest connected component over the total number of home devices in a three-dimensional network; (a) in small buildings; (b) in skyscrapers.

| Scenario  | small | historic | modern | ultra-modern |
|---|-------|----------|--------|--------------|
| Population density in persons/km <sup>2</sup>                         | 2260  | 8177     | 12500  | 25850        |
| Device density requirement in devices/km <sup>2</sup>                 | 380   | 700      | 3000   | 5000         |
| Market penetration requirement from simulations (power = 100mW)       | 0.168 | 0.086    | 0.24   | 0.193        |
| Calculated market penetration requirement (power = 1W, $\alpha = 5$ ) | 0.04  | 0.02     | 0.06   | 0.05         |

Table 3: Device density requirements vs. population density in different scenarios.

- Ultra-modern city center (e.g., Manhattan, New York City, USA) - large buildings with 50 floors.

Note that the values presented in Table 3 express a pessimistic approximation of the requirements for device density. Several conditions can accelerate the deployment of SOWER, as we discuss in the following subsection.

#### 4.4 Discussion

In all our measurements, we operated the IEEE 802.11 adapters at 100 mW, as this is the maximum power allowed in the considered city. In several countries (including the USA), the maximum transmission power for IEEE 802.11 wireless card is 1 W. As a results, the network can operate with a lower density of users.

To estimate this, let us model the transmission range of the device with a sphere. We increase the transmission power of the IEEE 802.11 wireless cards from 100 mW to 1 W.

The path loss exponent  $\alpha$  characterizes, how the communication distance depends on the transmission power:

$$d \sim P^{\frac{1}{\alpha}}$$

where  $d$  is the communication distance and  $P$  is the transmission power [26].

Thus, if we increase the transmission power from  $P$  to  $P'$ , we increase the communication distance as:

$$d' \sim \left(\frac{P'}{P}\right)^{\frac{1}{\alpha}} \cdot (P)^{\frac{1}{\alpha}}$$

In our case  $\frac{P'}{P} = 10$ . Assume that the path loss exponent  $\alpha$  is equal to 5, which represents a pessimistic approximation even in urban environments. Then the increase of the communication range is:

$$\frac{d'}{d} \sim (10)^{\frac{1}{5}} \approx 1.585$$

Since the volume of the covered area is  $V \sim d^3$ , the increase in terms of volume is:

$$\frac{V'}{V} \sim (10)^{\frac{3}{5}} \approx 3.981$$

The device density requirements for different scenarios decrease with the factor of the volume increase. We present the market penetration requirements for the increased transmission power in the last row of Table 3.

Interference affects connectivity as well; we discuss this issue in Section 6.

## 5. ROUTING

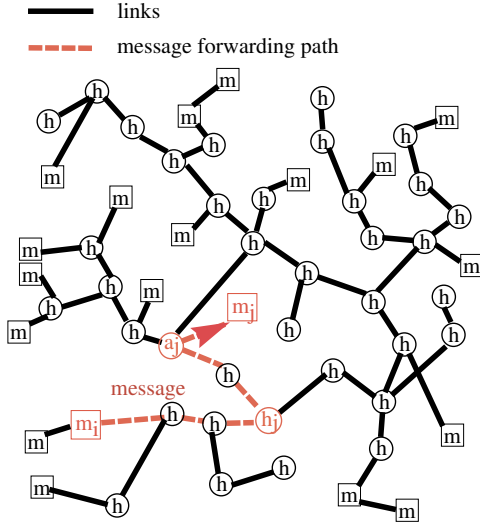
Having defined the conditions for connectivity, we now address the fundamental question of routing in SOWER.



SOWER requires a light-weight routing solution without route discovery and maintenance operations for each message. Clearly, if we used control messages for route discovery, we could send directly the data message instead of it. Current ad hoc routing protocols (e.g., AODV [25] or DSR [14]) are usually designed to establish a route for a data stream, thus they do have a route discovery and maintenance phase. In our proposal, routing is scalable, because it follows the “store-and-forward” principle. This principle is compliant with the delay tolerant property of the communication.

### 5.1 The Message Routing Protocol (MRP)

In order to enable multi-hop packet transmission, we propose a routing protocol that we call *Message Routing Protocol (MRP)*. MRP exploits the semi-static property of the network<sup>6</sup>. In our architecture, the mobile devices rely on the home devices to relay the traffic. We refer to the connected set of home devices as a wireless backbone. We illustrate the MRP mechanism in Figure 6.



**Figure 6: An example of message transmission using the Message Routing Protocol.** Here  $m_i$  and  $m_j$  stand for the sender and receiver, respectively. The home device of  $m_j$  is denoted by  $h_j$  and the current attachment point of  $m_j$  is denoted by  $a_j$ .

We assume that the device density is high enough to enable the set of home devices to be connected. We assume that the home devices maintain routing information among themselves with a distance vector routing protocol (for example with DSDV [24]) *without* periodic

<sup>6</sup>Note that MRP is similar to Mobile IP [23] in several aspects.

updates. Hence, an update message is only needed if a home device is removed or placed elsewhere. The application of such a scheme is appropriate, because home devices rarely move. Since short messages are delay-tolerant, they can be stored at any home device if a link is temporarily unavailable. A multi-path routing solution can also be applied to decrease the delay due to temporarily unavailable links. The investigation of such a multi-path routing scheme is the focus of our future work. In our current scheme, the mobile devices are not involved in the distance vector routing mechanism.

The following data are maintained at the home and mobile devices:

- **Wireless backbone routing table:** Each home device  $h_i$  maintains a routing table  $BRT_i$  that contains the address of the next hop to other home devices  $h_j$  in the network.
- **Attachment table:** Each home device  $h_i$  maintains an attachment table  $AT_i$ . The attachment table contains an entry for each mobile device  $m_j$  that is attached to home device  $h_i$ .
- **Location entry:** Each home device  $h_i$  keeps track of the mobile device  $m_i$  that belongs to it. This means that  $h_i$  registers the address of the attachment point  $a_i$  and updates it whenever a location update procedure is performed.
- **Attachment entry:** Each mobile device chooses a home device as an *attachment point*  $a_i$  and registers to it. The mobile device  $m_i$  stores the address of  $a_i$  in the attachment entry.

Now we describe the basic functions of the protocol:

- **Attachment of the mobile**

If  $m_i$  has several home devices within its radio range, it selects one home device as an attachment point  $a_i$ . Given the high density of home devices, it is reasonable to assume that  $m_i$  is always able to find an attachment point. The mobile device  $m_i$  registers to  $a_i$  with an ATTACHMENT REQUEST message. The attachment point  $a_i$  keeps track of all mobile devices attached to it. We assume that  $a_i$  periodically updates the corresponding entry based on the link layer neighbor discovery packets.

- **Location update**

A mobile device  $m_i$  sends LOCATION UPDATE packets to its home device  $h_i$ . The LOCATION UPDATE packet contains the address of the attachment point

of  $m_i$ . The home device  $h_i$  updates the attachment point's address in the location entry for  $m_i$ . There are two possible strategies for location update: (a) the mobile device periodically sends a **LOCATION UPDATE** packet to its home device  $h_i$  or (b)  $m_i$  sends a **LOCATION UPDATE** packet to  $h_i$  if it changes attachment point. We argue that mobility is not a dominant mechanism in our case, because devices are owned by individuals and most of them are static most of the day. Hence, the second strategy is more appropriate for SOWER.

- **Packet sending**

If a mobile device  $m_i$  wants to send a message to  $m_j$ , it addresses the message to the home device  $h_j$ . Then,  $h_j$  forwards the message to the current attachment point  $a_j$ . If the mobile is not attached anymore, than  $a_j$  sends a negative acknowledgement to  $h_j$ . In the latter case,  $h_j$  stores the message until it receives a **LOCATION UPDATE** packet from  $m_j$ .

It is important to emphasize that our routing proposal requires users to turn on their home devices, otherwise, they do not receive the messages addressed to them. Since the operation of the home devices is basically free (neither is it charged nor does it consume battery energy), the users are motivated to keep their home devices turned on all the time contributing to the common interest of all users.

## 5.2 Simulation of MRP

We developed a simulator in C to evaluate the performance of our routing protocol. The simulation was not feasible in a more sophisticated network simulator (e.g., in ns-2), because of the large number of nodes in the network. We investigated the following performance measures:

1. **Average goodput:** The average load per home device due to user messages.
2. **Average location update overhead:** The average traffic load per home device due to **LOCATION UPDATE** packets.

Location update constitutes the major part of the control overhead caused by the routing protocol. Most of the control overhead (e.g., neighbor discovery) is local, but location updates are routed from the mobile devices to their correspondent home devices.

In order to investigate traffic load on the wireless backbone, we first simulate a test network of 500 devices on an area of  $1 \text{ km}^2$ . We distribute the devices according to

the assumptions presented in Section 4. We assume that the users move according to the Gauss-Markov mobility model [2] with a randomness factor of 0.9; this approach provides a better model for pedestrian movements in a city than the commonly used random waypoint mobility model. We assume that all devices have a radio range of 75 meters, which is approximately the average radio range obtained from our field test results. We implemented MRP as the routing protocol, where mobile devices send location updates if they change attachment points. Simulation time is one whole day. During the simulation, we modify the parameters to distinguish three periods of the day: rush, calm and night hours. We adapt the message sending rate of the devices to the time periods: the message sending rate is 1, 0.1, 0.002 messages per minute for rush, calm and night hours, respectively (e.g., one message each minute, 10 minutes and 8 hours). Note that these message sending rates are arbitrarily chosen, but the number of messages sent in current cellular systems is much smaller, than the sending rate represented by these numbers. We assume that the user message length is 256 bytes (which corresponds to the size of an SMS message in GSM networks) and the length of a location update packet is 40 bytes.

Figure 7a shows the average traffic load at each home device during one day. Because the traffic load values are several orders of magnitude lower than the available link capacity, as we prove in Section 6, the message network scales well up to a city-size large scale network.

## 6. CAPACITY

In this section, we show that the capacity of SOWER is high enough to carry messages in an all-wireless network. We define *capacity* for a home device as the maximum available throughput.

We investigate the following performance measures:

1. **Capacity per home device:**

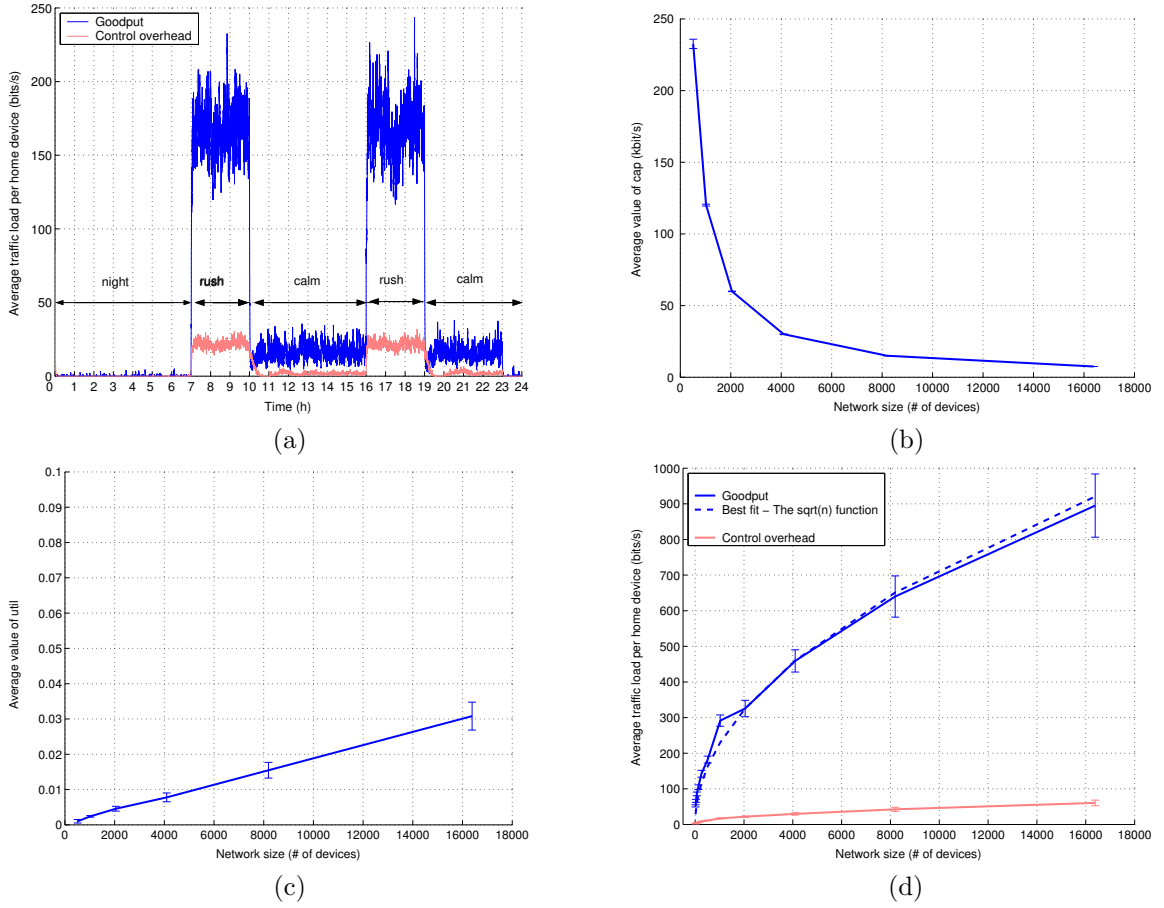
$$cap = \frac{\text{link capacity}}{\text{number of neighbors}}$$

where link capacity means the maximum possible throughput of the radio card in an isolated environment (i.e., if there are no other transmissions and there is no interference).

2. **Channel utilization per home device:**

$$util = \frac{\text{traffic load}}{cap}$$

where traffic load means the aggregate traffic that the home device has to transmit.



**Figure 7: Routing and capacity simulations; (a) Average traffic load per home device during one day of simulation; (b) Average value of capacity per home device ( $cap$ ); (c) Average channel utilization per home device ( $util$ ); (d) Average traffic load per home device as a function of network size.**

This notion of capacity per home device is meaningful, if the channel is not saturated, notably because there is a small probability of collisions. If the channel saturates, then the definition of throughput becomes more complicated. In the saturation case, the results in [1] can be applied.

We perform simulations for *one rush hour* in a metropolis scenario on a two-dimensional area of  $1 \text{ km}^2$ . Similarly to Section 5, we assume that the radio range is 75 meters. We increase the number of devices (and therefore the device density  $\delta$ ) exponentially from 512 to 16384 devices. As shown in Figure 7b, the maximum available channel capacity is inversely proportional with  $\delta$ . Because the set of home and mobile devices increases equally as  $\delta$  increases, the traffic load per home device remains constant. As a result, the channel utilization per home device increases linearly with  $\delta$ , as presented in Figure 7c.

Next, we perform a simulation to investigate the effect

of the network size on the traffic load. We increase the size of the network exponentially from 16 to 16384 devices; we also increase the size of the simulation area from  $125\text{m} \times 125\text{m}$  to  $4\text{km} \times 4\text{km}$  to keep the density  $\delta$  equal to  $1024 \text{ devices/km}^2$ . Figure 7d shows the average traffic load at each home device with increasing network size. Our results show that the average traffic load increases proportionally with  $\sqrt{n}$  as the network size increases.

The simulation results show that channel utilization is low even for large networks. The average traffic load per home device is some orders of magnitude lower than the capacity per home device. As a result, the links are generally not congested. Even if a link becomes temporarily congested, the “store-and-forward” principle of message transmission enables to store messages until this transient situation ends.

It is important to mention that we do not take the effect of collisions and interferences into account. As we

have shown in this section, the traffic rate is very small compared to the available maximum throughput. Thus, collisions occur rarely and their effect is negligible. As the data rate is low, the effect of interferences within the network is not very relevant either. The effect of possible interferences due to other networking technologies operating in the same ISM frequency band is more significant. But, due to the delay-tolerant property of the communication, messages can be stored at intermediate devices until the connection is restored. For a detailed analytical study on the effect of interference, the reader is referred to [4] and [28]. Due to these effects, the real capacity of SOWER is smaller than our simulation results. Let us emphasize, however, that we assumed a common link capacity of 1 Mbit/s. Current IEEE 802.11 technologies enable communication with a bitrate up to 54 Mbit/s. Thus, the available throughput can be much higher than the one we consider in our investigations.

## 7. ADDITIONAL TECHNICAL ISSUES

In this section, we address three issues that are also important in SOWER.

### 7.1 Access to the infrastructure and charging

If the device density is high enough in SOWER, then it can operate in a city without accessing an existing infrastructure. In this case, message forwarding can be performed within the network without charging. However, if the device density is not high enough or the network expands to several cities, SOWER can coexist with existing wireless networks, such as a cellular system. We assume, according to the traditional approach, that the sender of the message is charged if the message is transmitted to the destination using a cellular or a Wi-Fi network. If the message cannot be forwarded on SOWER, the sender of the message should be offered with the following options: (i) Pay for the delivery of the message using a cellular network; (ii) store the message until connectivity to the destination is restored or (iii) discard the message.

As we have shown in Section 5, users are naturally motivated to keep their home devices turned on. But a user may be tempted to modify the behavior of her home device to inhibit the relay function, as she does not obtain a benefit from it. In order to motivate users to refrain from doing so, a “virtual money” can be introduced (e.g., as described in [33]).

### 7.2 Security

Security is also a crucial issue in SOWER. It may be necessary to provide confidentiality and integrity of the messages. To fulfill these requirements, each message should be encrypted between the sender and the receiver using well-established cryptographic techniques.

In particular, the location update procedure of the routing scheme has to be secured to prevent attackers to send false location updates and redirect all messages of a given users to themselves.

A more challenging problem is how to secure routing, in order for example to prevent a malicious user from dropping or redirecting messages. The problem of secure routing has been extensively studied in recent years (e.g., in [12, 22]). The choice and adaptation of the most appropriate proposal is left for future study.

Another security issue is the following: A cellular operator could tamper with routing information to force users to pay for the message delivery. This has to be prevented in the network as well.

Furthermore, if charging is required, then a secure micro-payment system is required to manage the accounts of the users.

The issue of trust is closely related to security. Without the presence of an operator, the users have to maintain the network themselves. The operation has to be based on the emergence of mutual trust. Trust can be incorporated into the system as a reputation mechanism for example [19].

### 7.3 Addressing

In SOWER, a distributed addressing solution is needed to route messages correctly. Recently, several papers proposed addressing schemes for ad hoc networks. In particular, Eriksson, Faloutsos and Krishnamurthy describe a scalable dynamic addressing scheme in [5] that can be applied to SOWER as well. The solution is based on the separation of the node’s identifier from the routing address.

## 8. DISCUSSION

This section discusses practical aspects related to the initial deployment and to the business issues.

### 8.1 Deployment of the network

If one aims at the realization of a small scale network, like close communication among friends in a given area, then the deployment of the network is fast. Especially in small towns or villages, social groups tend to be close in terms of distance as well. If the envisioned network is large, then additional solutions are required to ensure communication until the device density reaches a satisfactory level.

In the following, we give an overview of additional solutions that can be exploited until the network is self-standing.

### 8.1.1 Delay tolerant messages

In the earlier phase of the network, it is possible that a user wants to send a message, but there is no connectivity with other devices. The same can happen if a user resides in an area, where no devices are operational. In conformance with the assumptions that were made in [6], one can imagine a messaging service that is delay tolerant. In this case, if the network is not connected, the devices store messages until they get a path to the destination. Additionally, as shown in [17], users can modify their trajectory if they receive a clear indication from the device on how to move (e.g., move closer to the window in a building). In this way, one can accelerate the message delivery process.

### 8.1.2 Interoperability with the existing infrastructure

Another possibility for overcoming the problem of insufficient connectivity in the network is to rely on the existing infrastructure to carry the messages.

- If no connectivity is available with the destination, the devices can exploit an access to a cellular network (or to a Wi-Fi access point). In this case, the user should be notified that she will be charged by the operator of the infrastructure network.
- High speed Internet connections are more and more popular. According to [39], in October 2003 in the U.S., 60% of the households had an Internet connection and according to [40] 40 % of them were high-speed. Internet connections provide another solution to connect unconnected areas.

The deployment of the network can be faster if a manufacturer provides dual-mode devices. Such a device could be a cellular mobile phone that is able to operate in ad hoc mode as well. There are several products that already provide access to both cellular networks and WLANs. We mention a subset of them such as: the Sierra Wireless AirCard 555 [41], the Nokia GPRS / WLAN card - (D211 / D311) [42] and the GlobeTrotter COMBO PCMCIA card for WLAN / GPRS / GSM [43].

## 8.2 Business issues

In this subsection, we derive a financial motivation of the users. We base our study on data acquired for the United Kingdom. We use the real data to justify the need for free message sending from the user's point of view.

The population of UK is 59 million. As mentioned in [44], the mobile penetration in the UK is about 0.74 (the number of registered users is 43.5 million). According to [45], there has been 20 billions of SMS sent in 2003.

We assume that Pareto's 80-20 rule applies to SMS messaging, namely that 20 per cent of the users send 80 per cent of the messages. In general, the price of an SMS message is 0.10 pounds. Thus, we can calculate the SMS requirements in terms of both number of SMS messages sent and price paid for each type of users (i.e., frequent senders and rare senders) as shown in Table 4. We see that for frequent users, the SMS costs in one year can easily cover the costs of buying a mobile and a home device. Thus, our proposal is cost-effective for them.

## 8.3 Operators' strategy

Clearly, the prospect of SOWER can be perceived as a threat by cellular operators, as it is susceptible to jeopardize the revenue obtained from the frequent SMS users. However, it can also be an opportunity: the operators can try to surf on this potential new fad by being the enabling company that deploys the first "home" devices to bootstrap connectivity; they would in any case remain the unavoidable solution for long-range (meaning inter-city) connectivity. This strategy would be similar to the one adopted by several incumbent operators with respect to the deployment of hot spots.

## 9. CONCLUSION

In this paper, we have studied SOWER, an all-wireless, user-operated alternative to cellular networks for the provision of SMS in urban environments; we relied as much as possible on the real data of propagation measurements and of city topology. The conclusions are very encouraging: (i) the city-wide connectivity can be achieved even with a modest market penetration, in all the city scenarios we have studied; (ii) the routing protocol we have proposed (MRP) has negligible overhead, especially at rush hours; (iii) the solution motivates users to contribute to the network; and (iv) the capacity is sufficient to support messaging, owing to the modest bandwidth needs of SMS with respect to the high bitrate of the wireless links.

We believe that the feasibility (and possibly the real deployment of SOWER in some cities) will have a beneficial influence on the pricing of SMS: this prospect will have an impact on the pricing of messaging similar to the impact that Voice over IP has had on the pricing of conventional voice service.

In terms of future work, we intend to pursue our measurement campaign in order to corroborate our simulation results in specific scenarios. We will further study the charging and security issues discussed in Section 7. We also intend to implement MRP and study its behavior in a prototype setting. Finally, we will study the usage of SOWER in emergency situations (e.g., disaster recovery).

| <i>Parameter</i> | <i>Frequent senders</i> | <i>Rare senders</i> |
|------------------|-------------------------|---------------------|
| Number of users  | 8.7 millions            | 34.8 millions       |
| SMS sent/year    | 16 billions             | 4 billions          |
| SMS/day/user     | 5                       | 0.315               |
| SMS/year/user    | 1839                    | 115                 |
| price/year/user  | \$334 / £184            | \$22 / £12          |

**Table 4: SMS data in the UK for 2003**

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